QCD and B Physics Results at CDF

Presented for the CDF Collaboration

by

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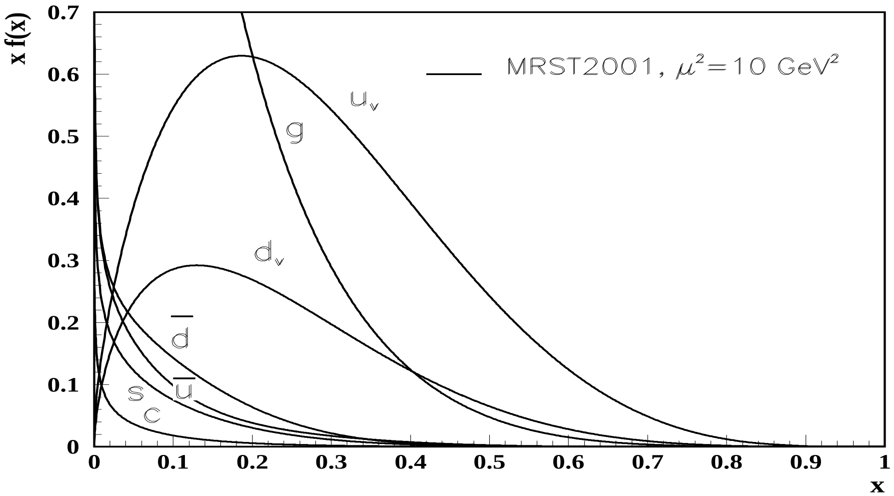
QCD Topics

- *Inclusive Jet Cross Section*
- *Jet Shapes Measurements*
- *DiPhoton Mass Distribution*
- *Diffractive Structure Function*
- *Inclusive b Jet Production*

Studying high energy interactions tests our understanding of the Standard Model $\rightarrow$ *searches for new physics....*

The Tevatron is the world's highest energy collider
Probing distance scales of $\sim 10^{-17}$ cm



Particle structure is parameterized with Parton Density Functions (PDFs)

$\rightarrow$ *Gives the probability of probing the constituent quarks*

x : momentum fraction carried by struck parton

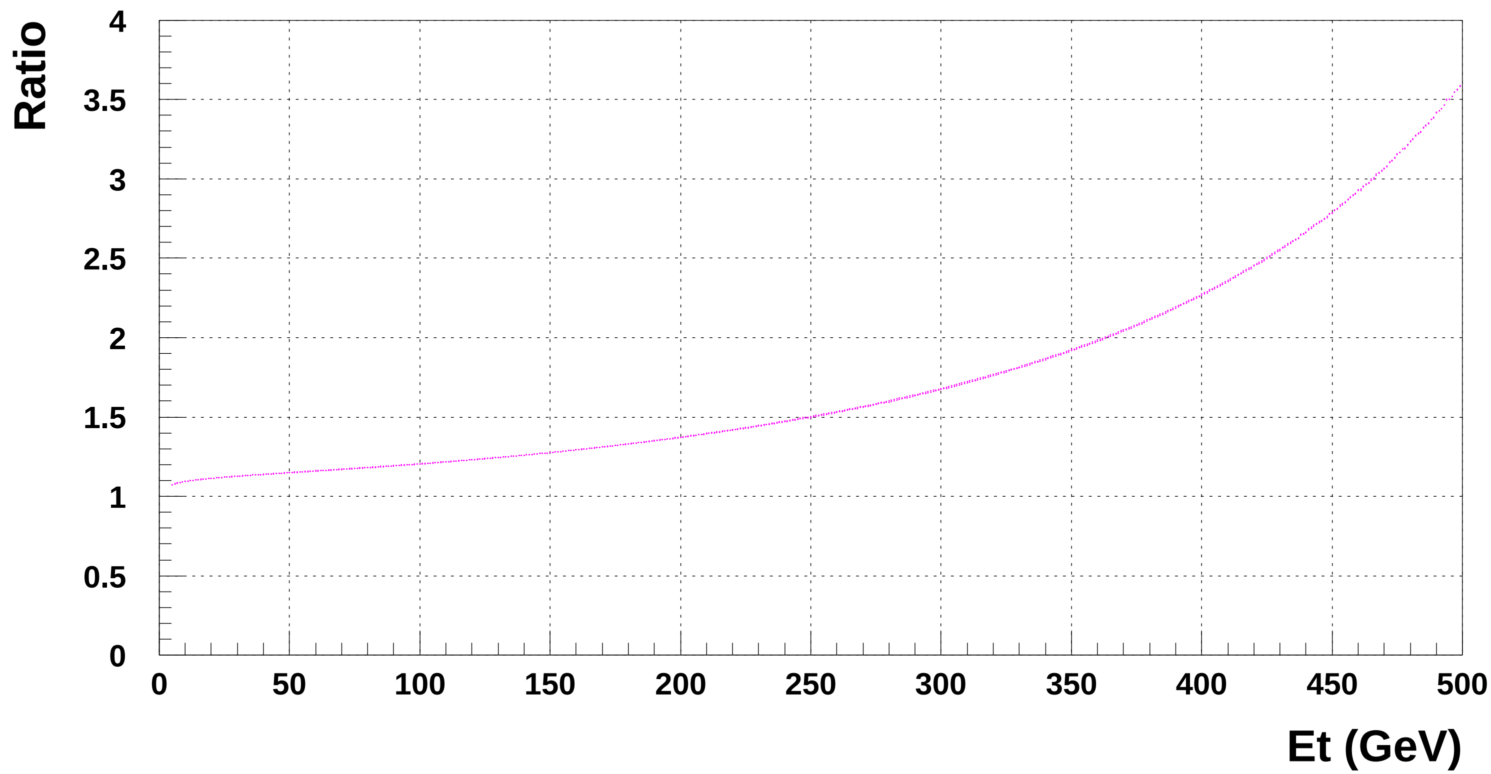
Q^2 : the square of the momentum transfered to the target $p(\bar{p})$

PDFs are fundamental inputs to calculations describing collider phenomenology

Improved PDFs allow more precise calculations that will be needed not only at the Tevatron but also at the LHC and future experiments

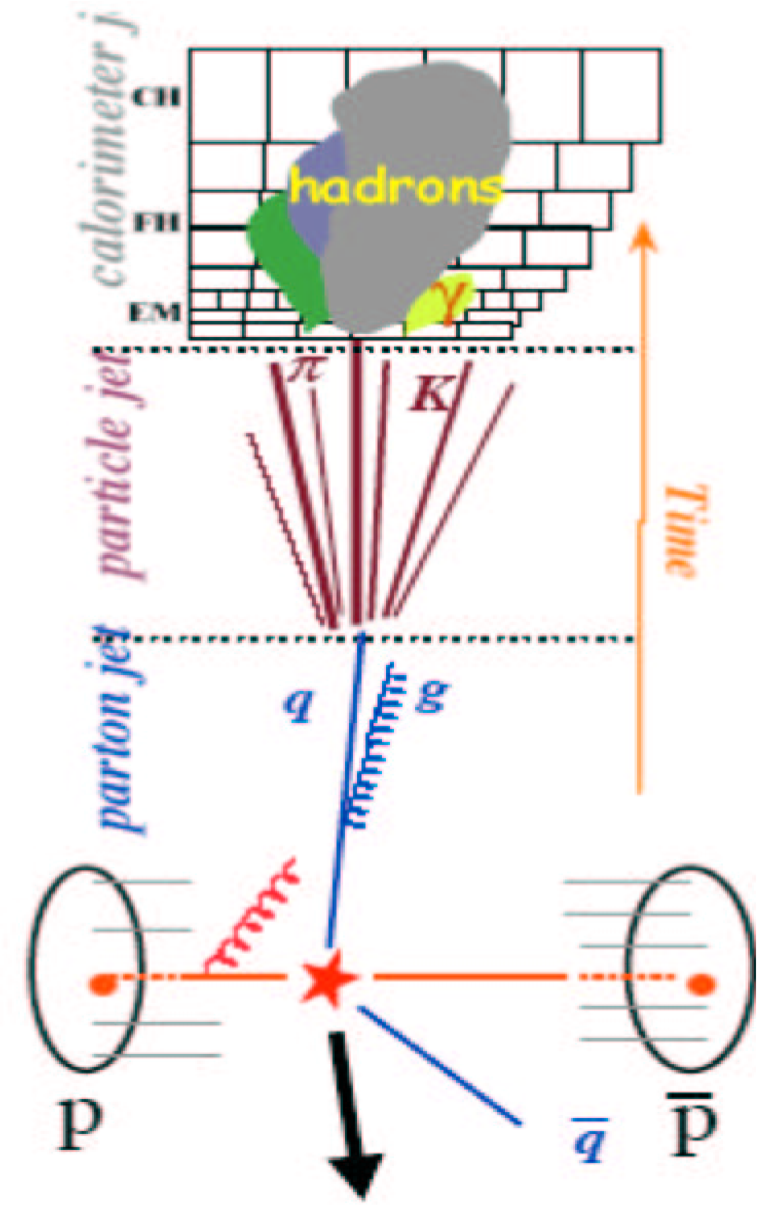
The increase in the center-of-mass energy from 1.8 to 1.96 TeV results in more than a 3$\times$ increase in the cross section for high energy jets (jets with $E_T > 500\text{GeV}$)

Jet cross section ratio $\sigma(\sqrt{s} = 1.96\text{TeV})/\sigma(\sqrt{s} = 1.8\text{TeV})$



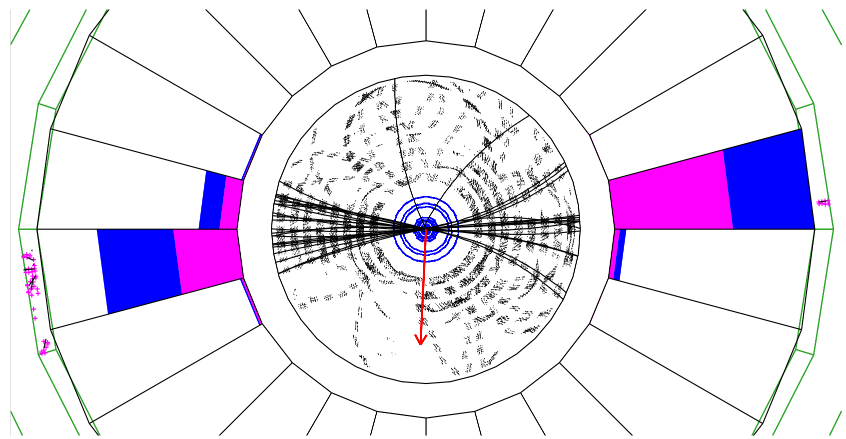
$\rightarrow$ *Able to probe shorter distances and have greater statistics*

Reconstructing Jets From Partons

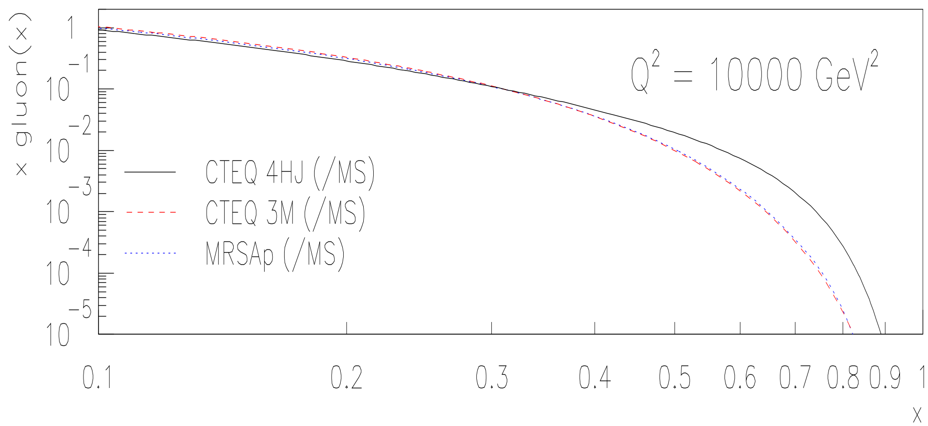


"Bare" quarks are not observable

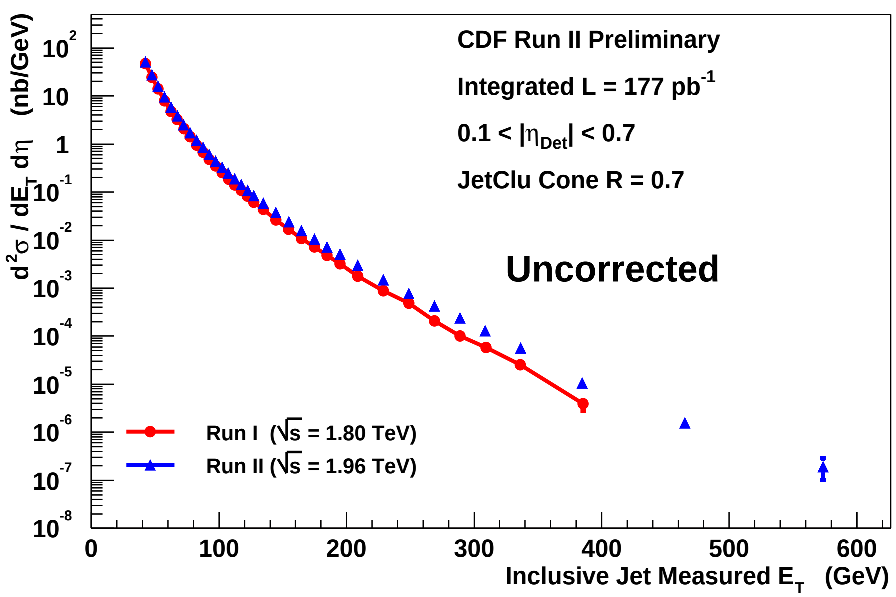
→ we measure long lived particles produced through hadronization



The run I inclusive jet cross section was larger than theory expectations at high E_T



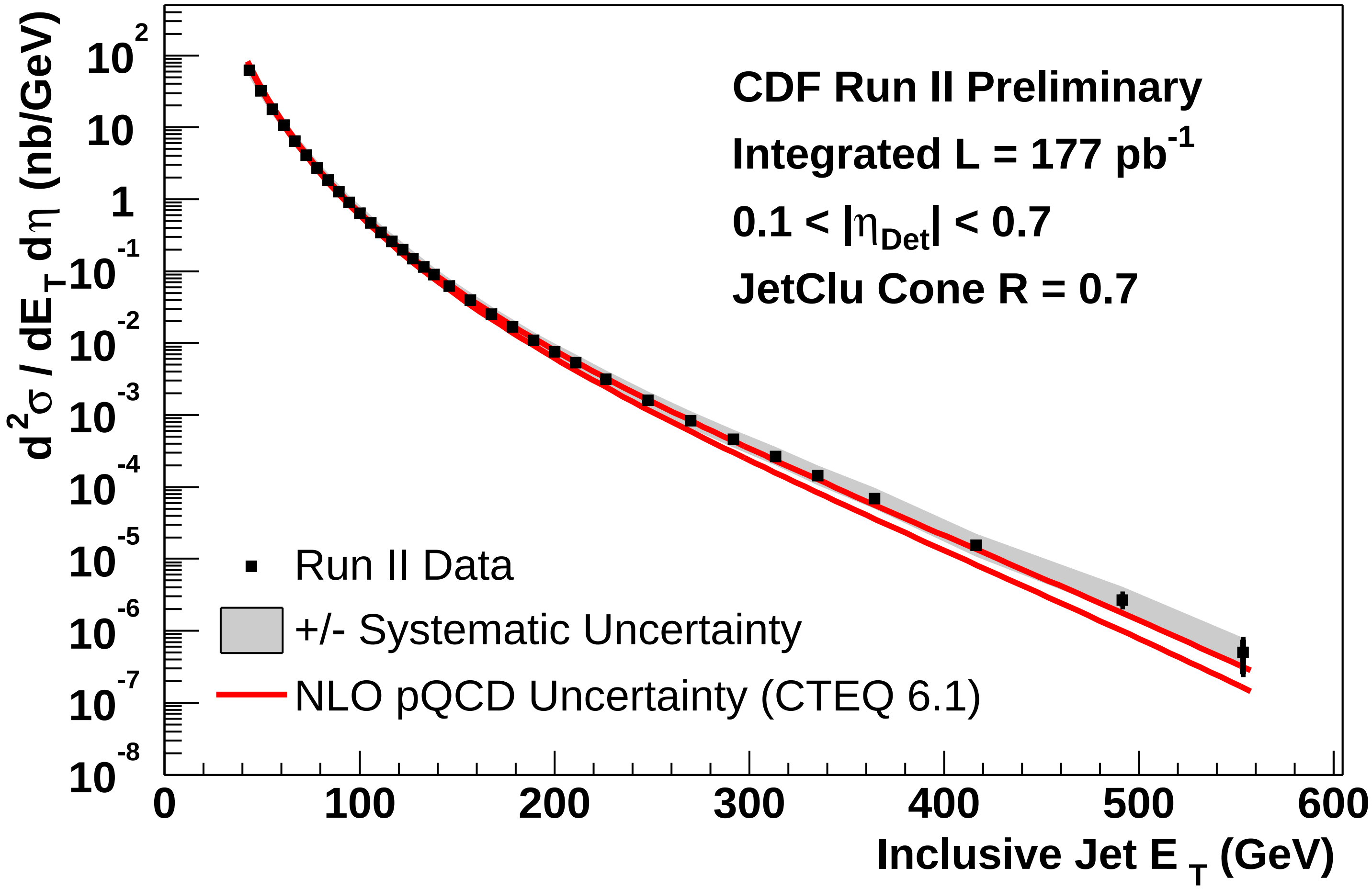
Excess accommodated by modified PDFs having an enhanced gluon density at high x



In RunII, the increased center-of-mass energy enables us to extend our reach by about 200 GeV

$\rightarrow$ *Probing even smaller distances with higher precision*

Inclusive Jet Cross Section

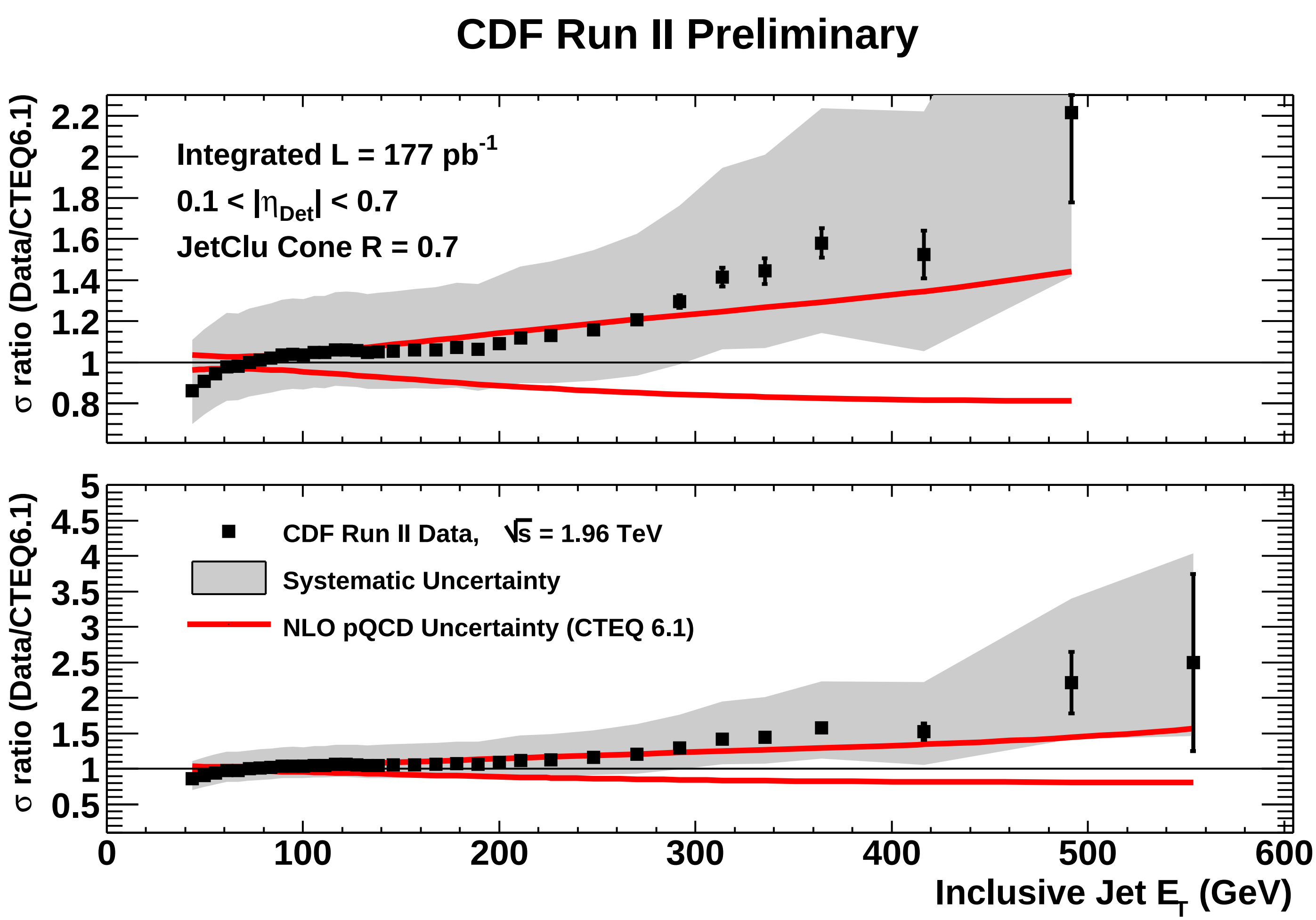


→ *Test of QCD over 9 orders of magnitude*

→ *Highest E_T probes the shortest distances*

The CTEQ 6.1 PDF has an enhanced gluon density at high x

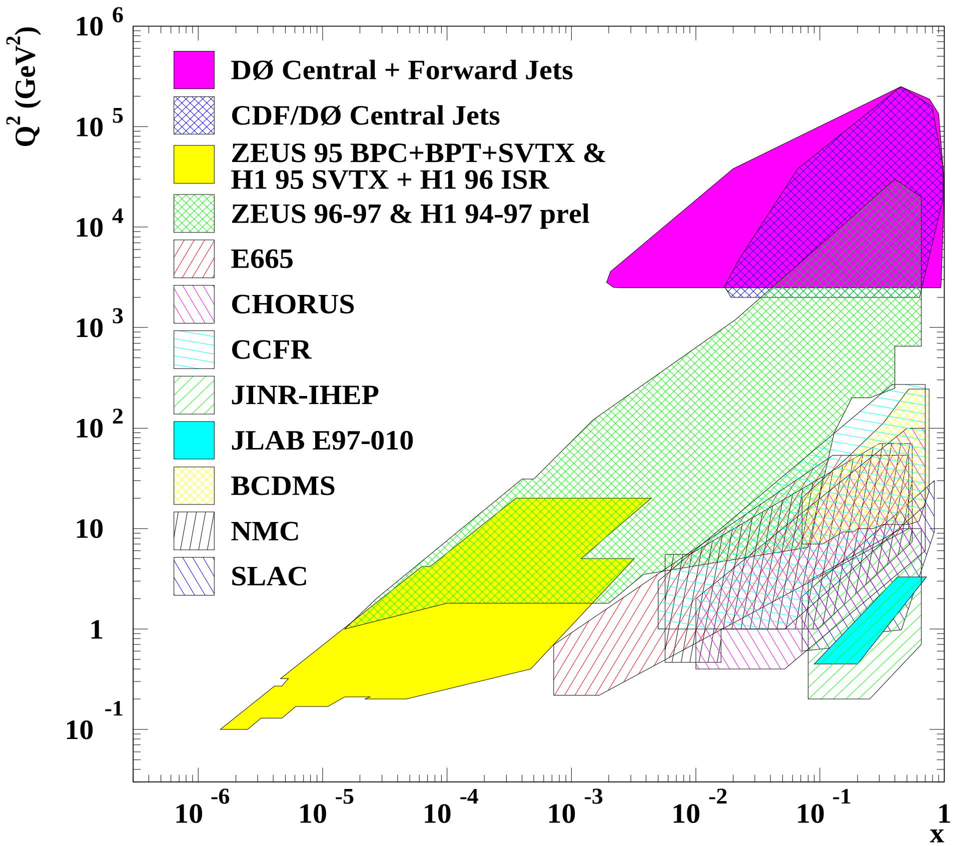
Run I Jet data was used in the fit



Particle level measurement compared with parton level calculation

→ *Energy scale is the dominant source of systematic uncertainty, can expect this to improve...*

The Tevatron operates in a kinematic region complementing existing and previous experiments and provides unique capabilities



Run I measured region

The parton momentum fraction can be reconstructed from the jet's transverse energy, E_T, and pseudorapidity, η, by

$$x_{12} = \frac{E_T}{\sqrt{s}}(e^{\pm\eta_1} + e^{\pm\eta_2})$$

An approximation of the four momentum transfer, Q^2, in the interaction is

$$Q^2 = 2E_T^2 \cosh^2\eta^*(1 - \tanh\eta^*)$$

$\rightarrow$ *Best place to study the high x gluon content of the proton*

Study of Jet Shapes In Inclusive Jet Production

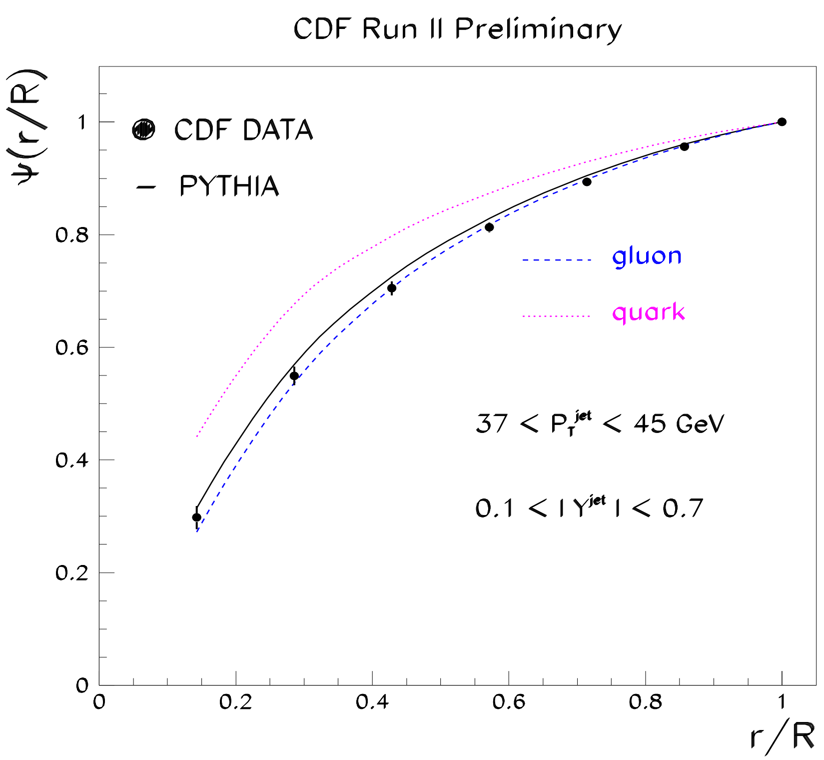
Jet shape is governed by multigluon emission from struck parton

$\longrightarrow$ *Provides tests of multiparton shower models*

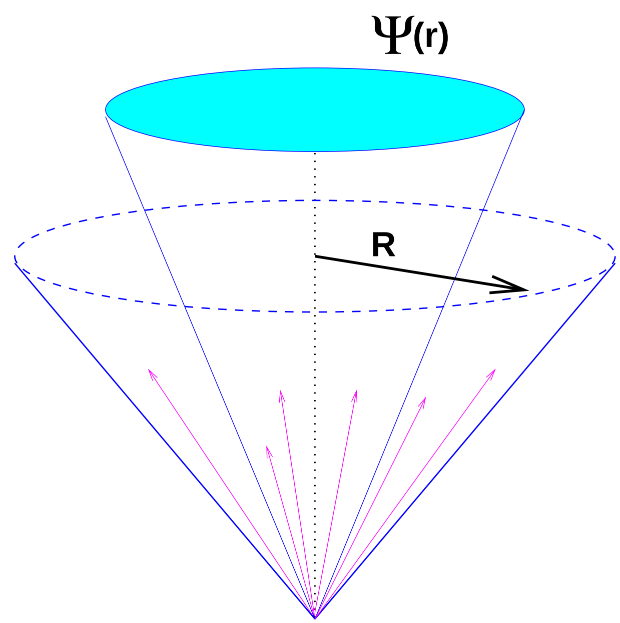
$\longrightarrow$ *Sensitive to the quark/gluon final state mixture*

$\longrightarrow$ *Sensitive to the underlying event*

Integrated Jet shape

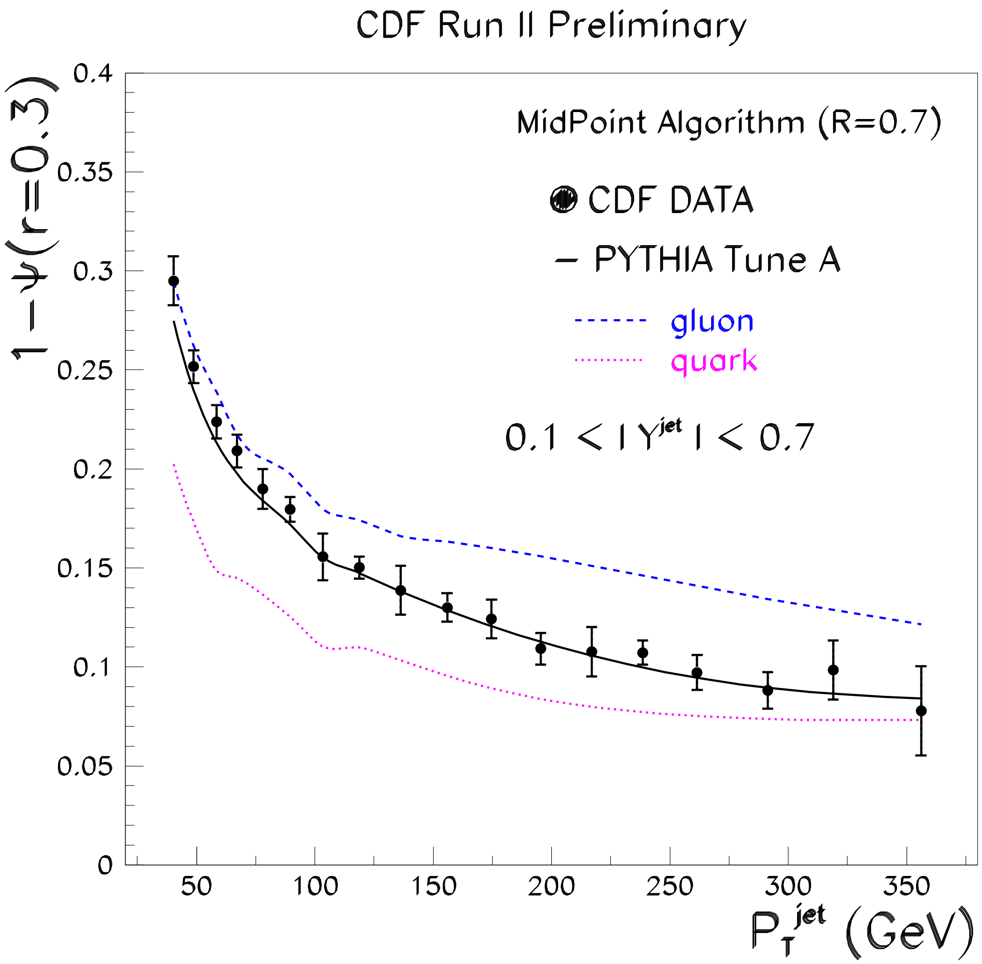


$$\Psi(r) = \frac{1}{N_{jets}} \sum_{jets} \frac{P_T(0,r)}{P_T(0,R)}$$



How does the jet shape evolve with increasing p_T?

Look at the fraction of the jet transverse momentum found outside of the fixed cone radius ($r = 0.3, R = 0.7$) versus Jet p_T



Shows the running of the strong coupling constant with increasing hard scale

Able to study the evolution of the quark/gluon content of the jet

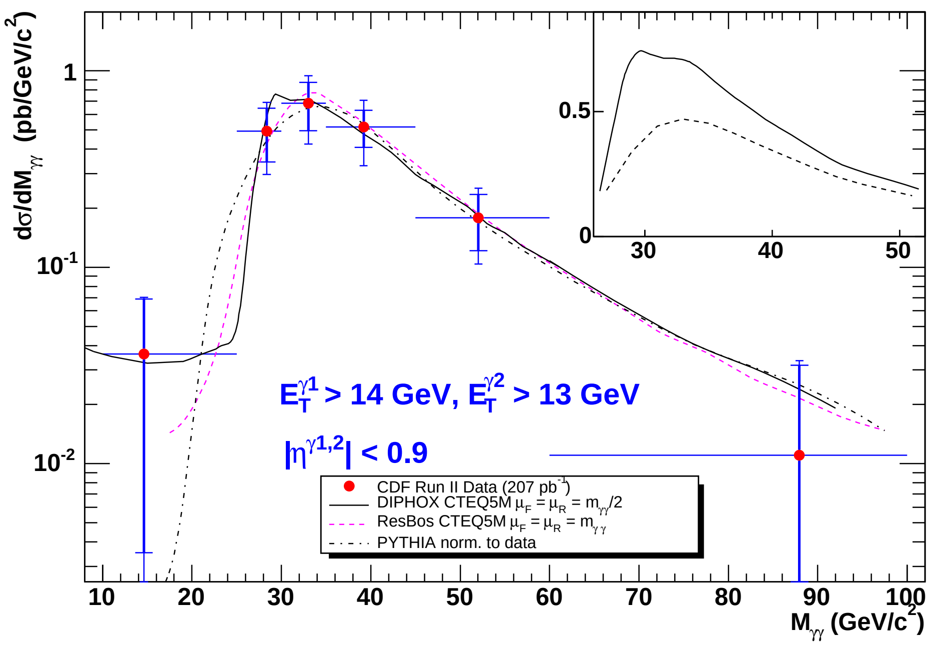
Tuned Pythia describes the data well...

DiPhoton Mass Distribution

Diphoton final states are important signatures for many interesting physics processes

For example, at the LHC one of the main discovery channels for the Higgs is through the $\gamma\gamma$ final state

QCD production of $\gamma\gamma$ is large compared to most new physics and needs to be understood prior to any possible discoveries

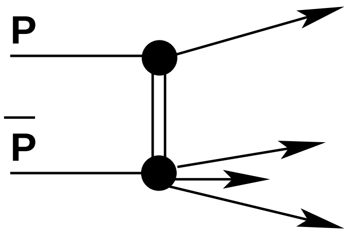


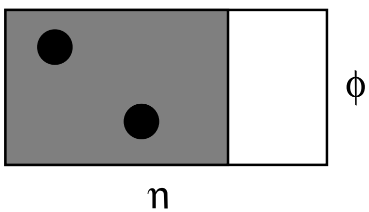
Data compared to the next-to-leading order QCD predictions of DIPHOX and ResBos

Inset shows the NLO cross section with and without the gg term

→ *Soft gluon emission and NLO fragmentation are important*

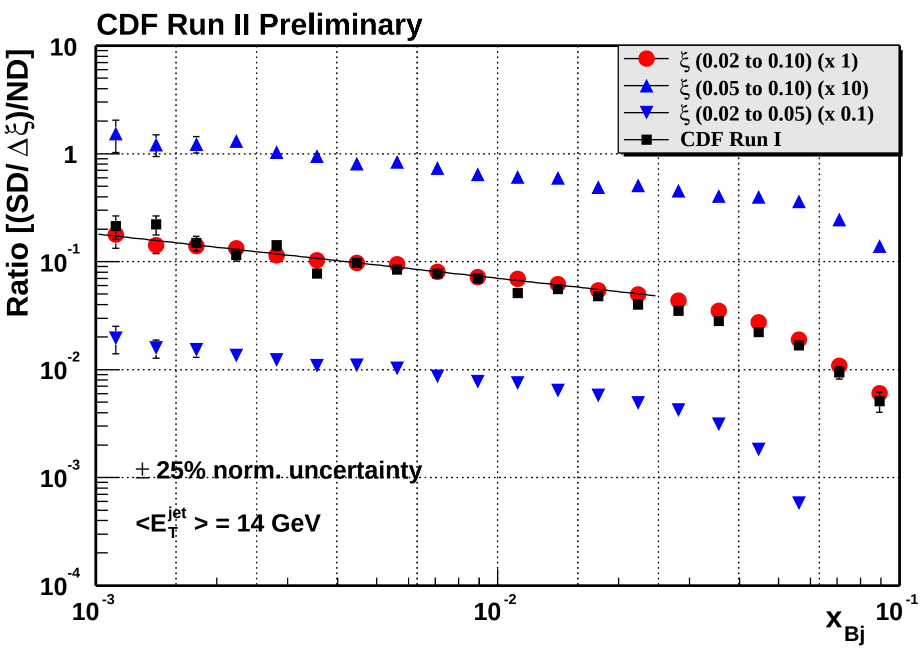
Is the Tevatron and HERA Pomeron the Same?





Diffractive systems with a mass greater than 450 GeV can be produced at the Tevatron compared to 70 GeV at HERA

The measured diffractive structure function (F_2^D) at the Tevatron is different in shape than at HERA and smaller by about an order of magnitude



Reproduce the Run I result using single diffractive dijets

In Run II we are able to measure at lower values of the recoil p ($\bar{p}$) fractional momentum loss ξ and higher Q^2

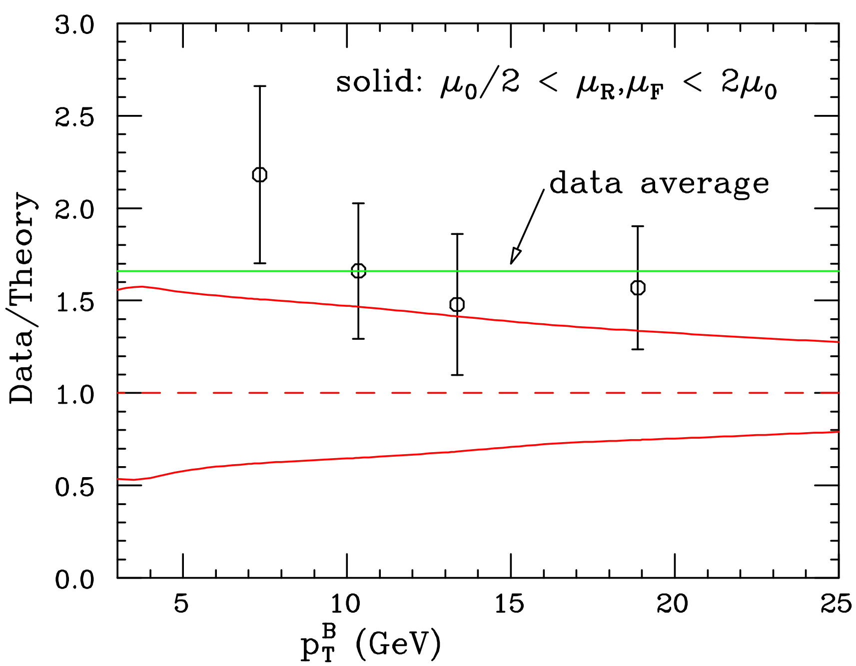
→ *Evolution from low to high Q^2 needs to be understood*

Does the b quark production rate agree with QCD?

Run I inclusive b jet production cross section measured by both CDF and DØ is $\sim 2\times$ the rate predicted by the Standard Model.

$\rightarrow$ One of the few cases where the experimental results and QCD predictions are not in good agreement

$d\sigma(p\bar{p} \rightarrow B^+X)/dp_T$ vs $p_T(B^+)$



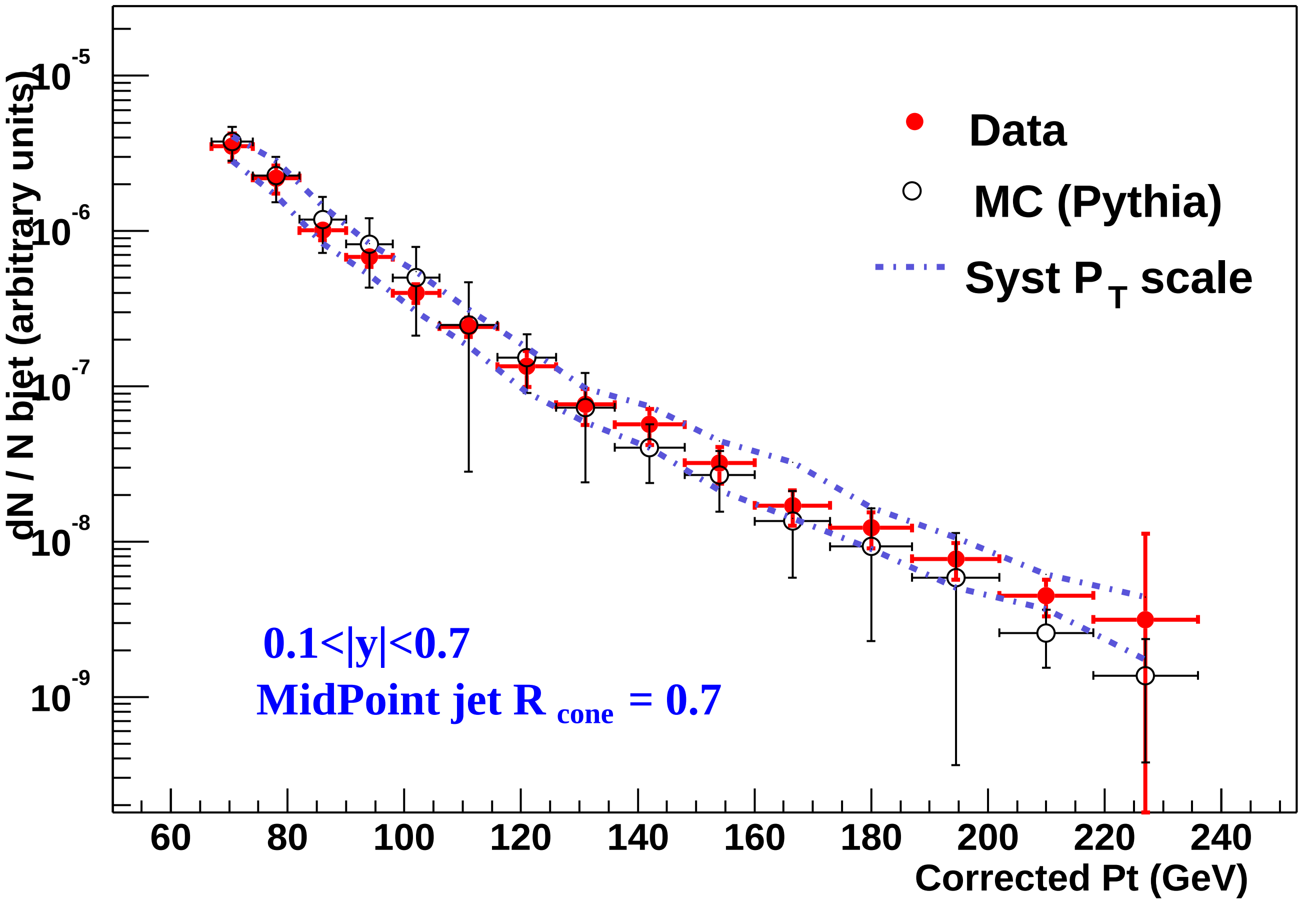
hep-ph/0204025 (M. Cacciari, P. Nason)

A more careful theory calculation was performed using up-to-date information on the B fragmentation function

Resulted in better agreement.

But... data is still above the prediction

Run II - Inclusive b Jet Production Rate

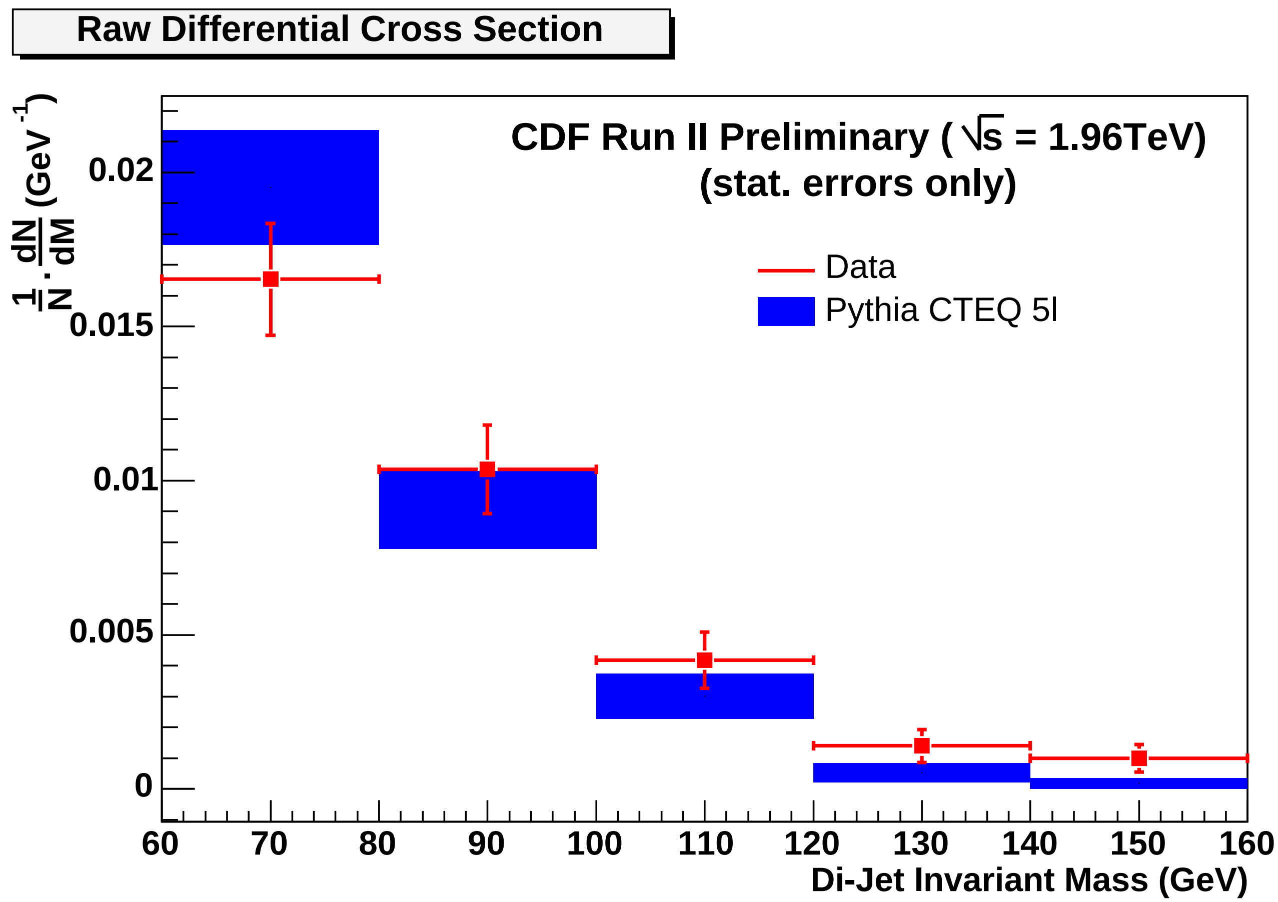


Requires at least one central $(0.1 < |\eta| < 0.7)$ b tagged jet

MC normalized to the data $\rightarrow$ *QCD describes the shape*

$\rightarrow$ *Expect more precise measurements and theory comparisons*

New physics may show up as a "bump" in the $b\bar{b}$ DiJet mass spectrum



Invariant mass constructed from two central b tagged jets

→ *Currently only looking at the lowest* E_T *sample*

Publications in Progress

- Study of Jet Shapes in Inclusive Jet Production
Under internal publication review.

- Diphoton Production Cross Section
Under internal publication review.

Work In Progress

- Inclusive Jet Cross Section using Cone Algorithms
- Inclusive Jet Production using Kt Algorithm
- Inclusive B-Jet Production
- bb-bar pair Production
- Gamma+heavy Quark Production
- W+jets Production Cross Section
- Diffractive Dijet Production
- Search for New Particles Decaying into DiJets
- Exclusive J/Psi Production
- Jet Evolution and Underlying Event Studies
- PYTHIA MC Tuning

B Physics Results

- *Measurement of B Hadron Masses in Exclusive J/ψ Channels*
- *B Meson Lifetimes From Exclusive Decays*
- *Search for Rare Decays $B_{d,s} \to \mu^+\mu^-$*
- *First Observation of $B_s \to \phi\phi$*
- *$B \to VV$ Polarization Amplitudes*
- *Measurement of B^0 Oscillations*
- *Observation of the $X(3872)$ at CDF*

One of the main goals of the B physics program is to test the Standard Model (Cabibbo-Kobayashi-Maskawa) of weak quark mixing and CP violation

Measurements of B hadron decay rates, observation of $B^0 - \bar{B}^0$ mixing and CP asymmetry in the B and K sectors provide the most precise measurements of the CKM matrix elements

The degree of mixing can be characterized by:

$$x \equiv \frac{\Delta m}{\Gamma}$$

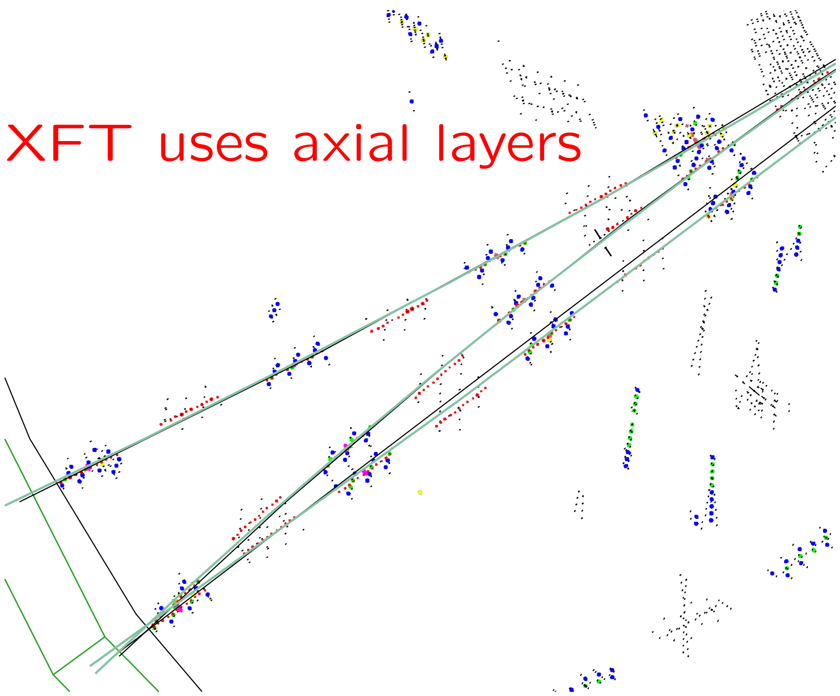
Δm, mass difference between the heavy and light B meson states

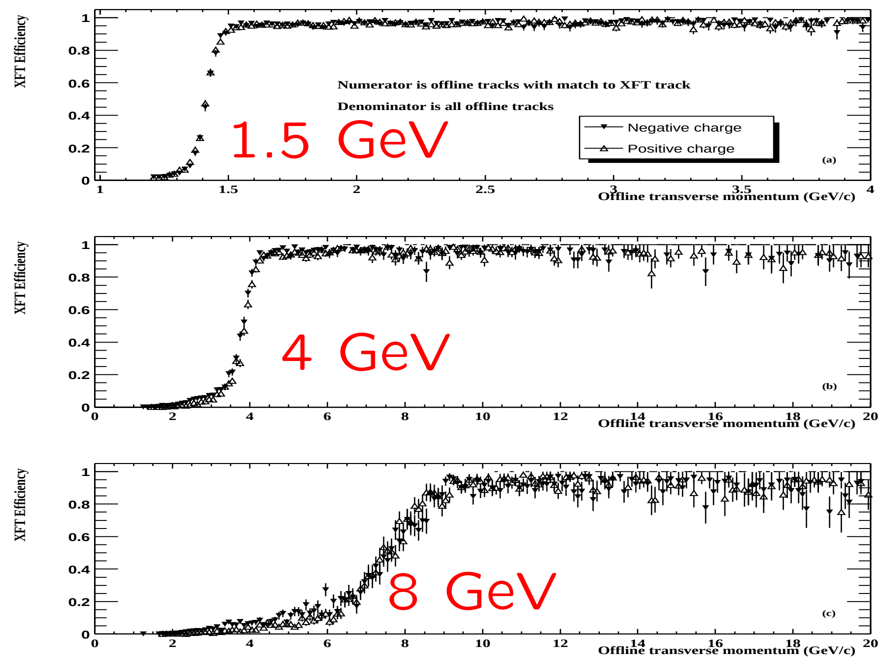
$\Gamma = \hbar/\tau$, where τ is the average lifetime of the states

$D\emptyset$ and CDF at the Tevatron are currently the only places where B_s mesons and Λ_b baryons can be studied

Extremely Fast Tracker (XFT Trigger)

Tracking trigger at L1! Enhances our physics capabilities, able to collect large samples used for in situ calibration.





XFT tracks (green) compared with offline tracks (black).

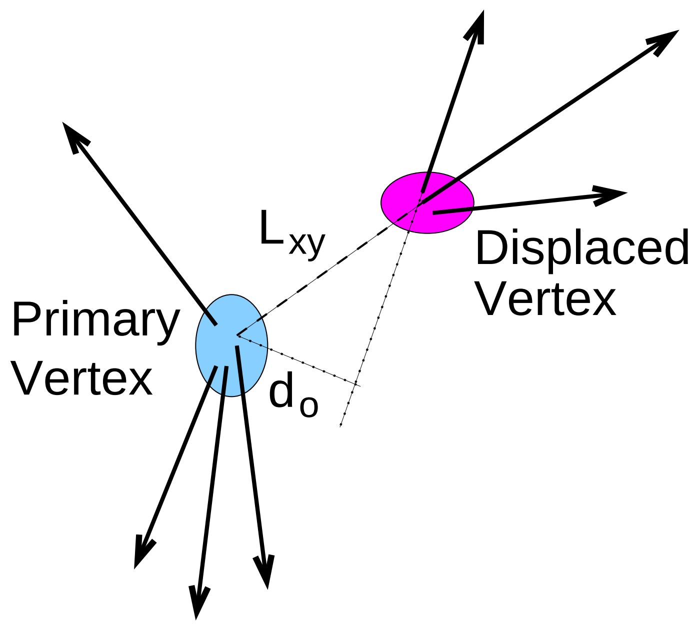
Performance exceeds design specification.

$\rightarrow$ Measured momentum resolution $(\Delta p_T/p_T^2) = 1.65\%\, p_T$ (GeV/c)

$\rightarrow$ Measured angular resolution 5.1 mR.

Silicon Vertex Trigger (SVT) at Level 2

Selecting events with a secondary vertex at the L2 trigger stage



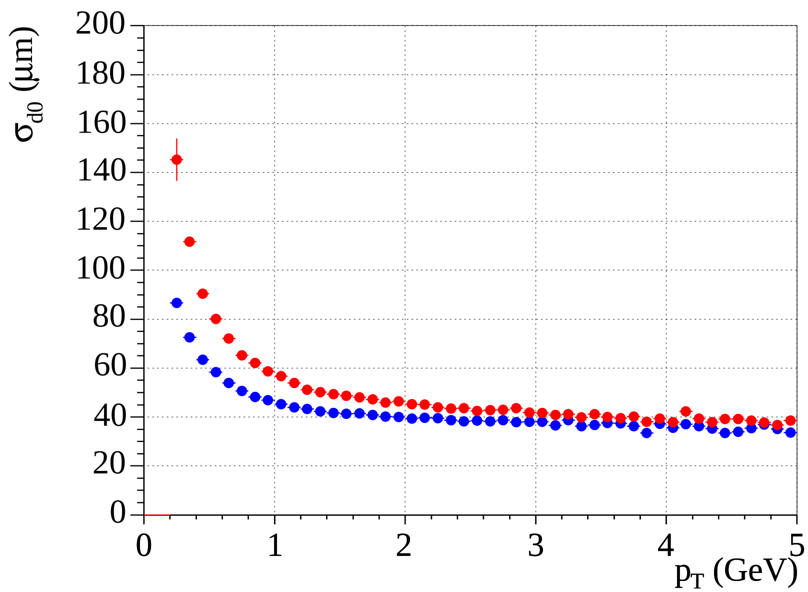
Combines silicon hits with L1 tracks (XFT)

b quarks have lifetimes
$\tau(b) \sim 1.5ps \quad (c\tau \sim 450\mu m)$

Using impact parameter (d_o) to detect secondary vertexes at the Level 2 trigger significantly increases both our physics potential and calibration sample

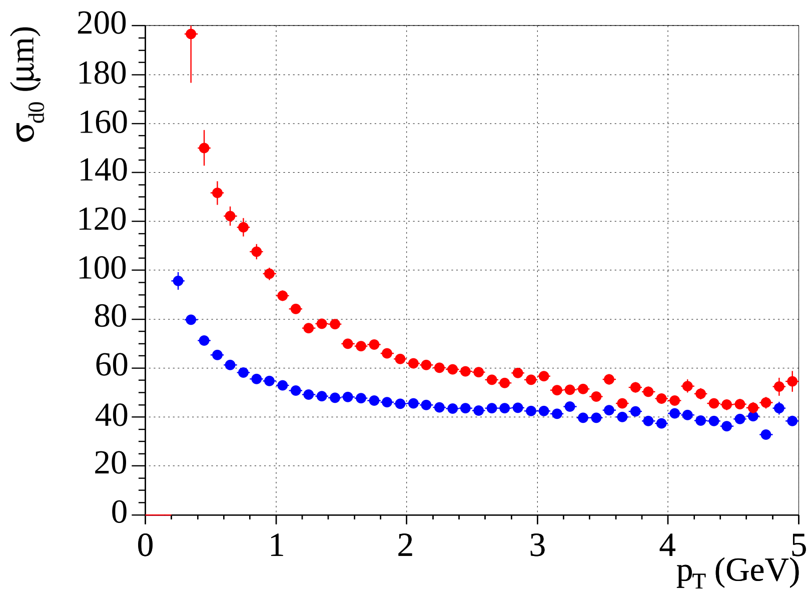
Including hits from the innermost silicon layer (L00) significantly improves the impact parameter, $d0$, resolution for tracks with low p_T and for tracks that traverse more material

Silicon only regions



Tracks with $|\eta| < 1$ *and* $|z| < 8$cm

SVX bulkhead region:

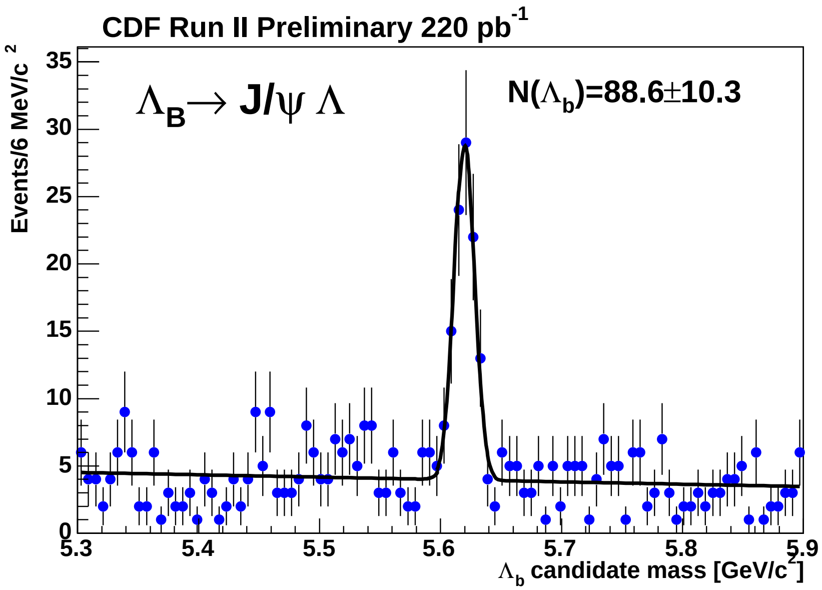


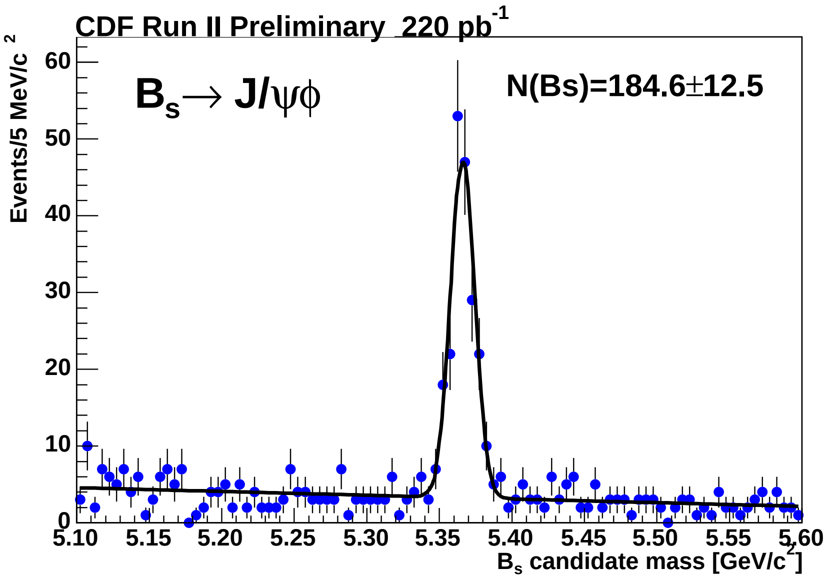
Tracks with $11 < |z| < 19$cm

Improves the proper time resolution (from 67 $\rightarrow \sim$ 50fs)

$\rightarrow$ *Essential for* B_s *mixing measurements*

B hadron masses in exclusive J/ψ channels





$$m(B^{+}) = 5279.10 \pm 0.41(stat) \pm 0.36(sys)\mathrm{MeV/c^2}$$

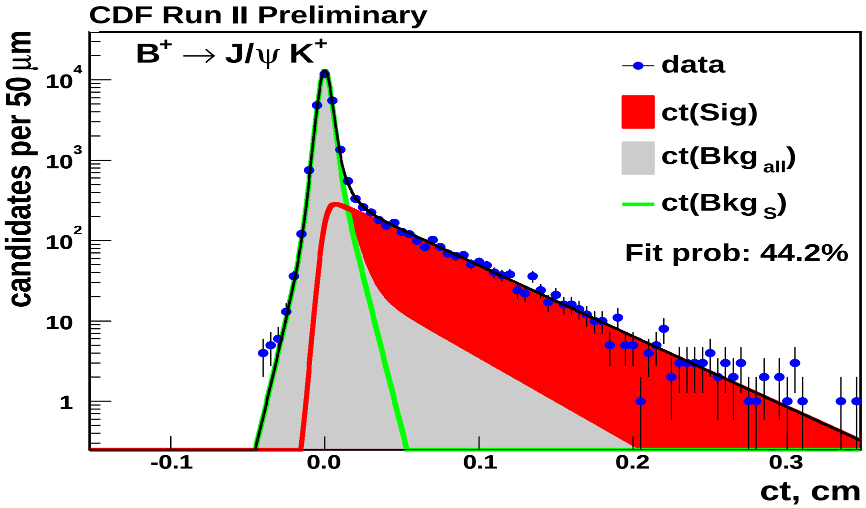
$$m(B^{0}) = 5279.63 \pm 0.53(stat) \pm 0.33(sys)\mathrm{MeV/c^2}$$

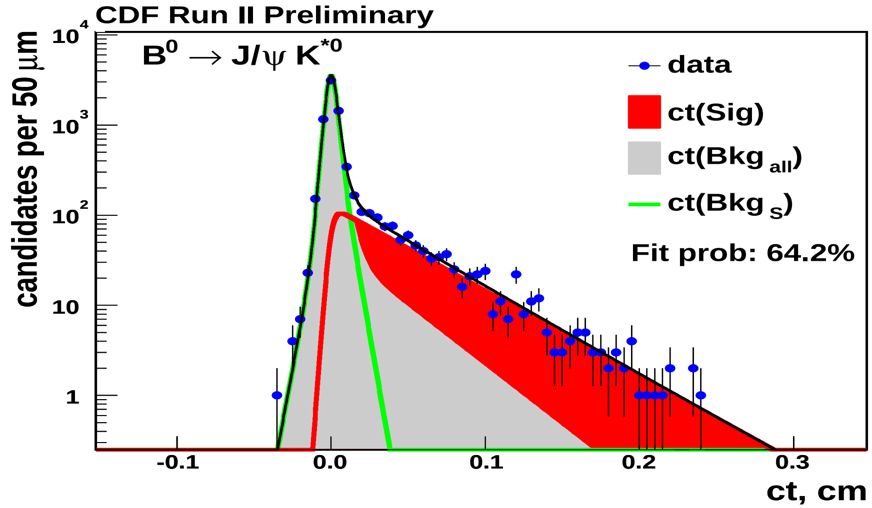
Worlds best measurement for $m(B_s^0)$ and $m(\Lambda_b)$

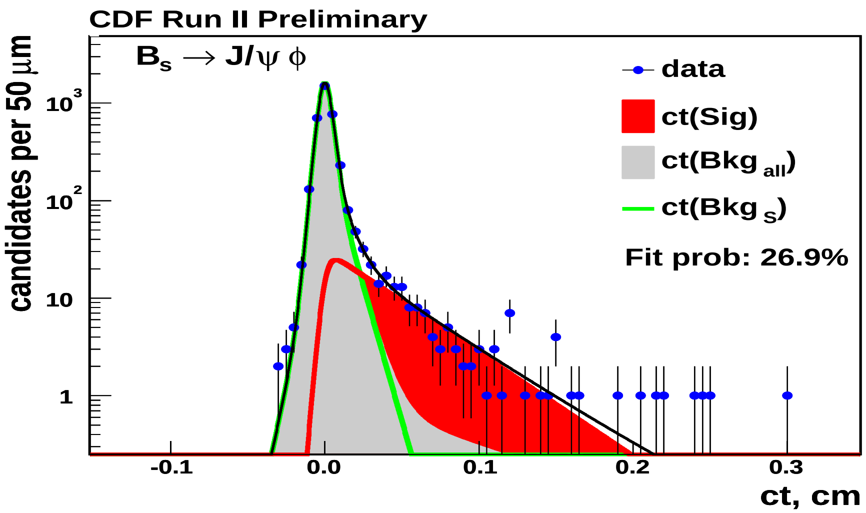
$$m(B_s^{0}) = 5366.01 \pm 0.73(stat) \pm 0.33(sys)\mathrm{MeV/c^2}$$

$$m(\Lambda_b) = 5619.7 \pm 1.2(stat) \pm 1.2(sys)\mathrm{MeV/c^2}$$

B Meson Lifetimes From Exclusive Decays







$$\tau_{B^+} = 1.662 \pm 0.033(stat) \pm 0.008(sys)ps$$

$$\tau_{B^0} = 1.539 \pm 0.051(stat) \pm 0.008(sys)ps$$

$$\tau_{B_s} = 1.369 \pm 0.100(stat)^{+0.008}_{-0.010}(sys)ps$$

Systematic uncertainties understood to the $\mathcal{O}(1\mu m)$ level

Results are competitive with the Particle Data Group

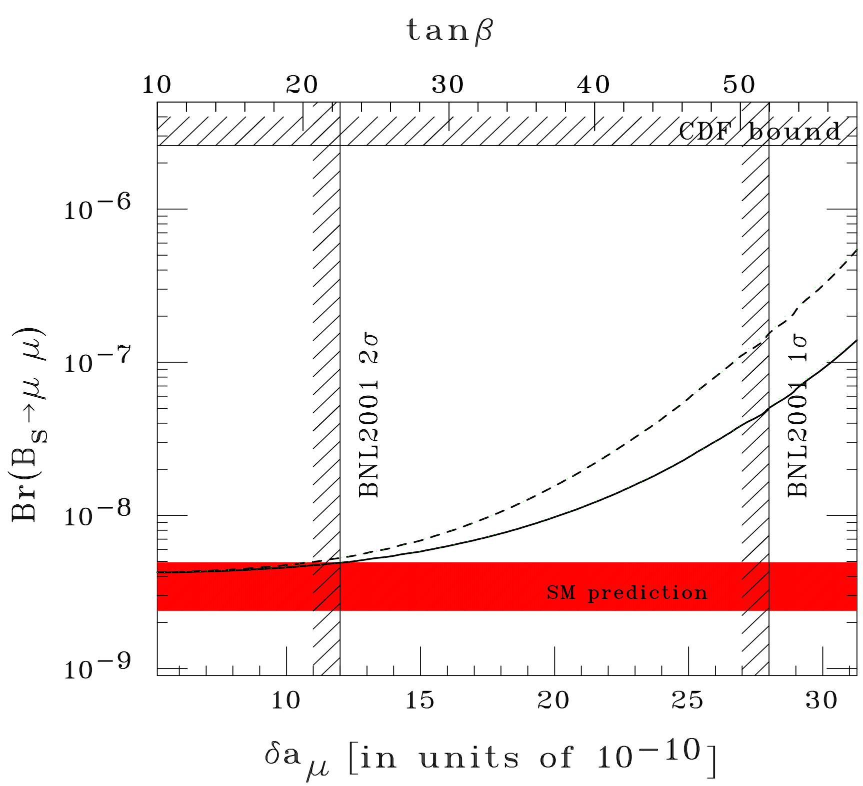
$\rightarrow$ One of the components needed for a measurement of $\Delta\Gamma_s$

Search for Rare Decays $B_{d,s} \rightarrow \mu^+\mu^-$

Standard Model expectation for BR($B_s \rightarrow \mu\mu$) is $\sim 3.8 \times 10^{-9}$

Many extensions to the standard model predict an enhancement of the BR by *1 to 3 orders of magnitude*

$\rightarrow$ *There is a lot of theoretical interest in this number...*

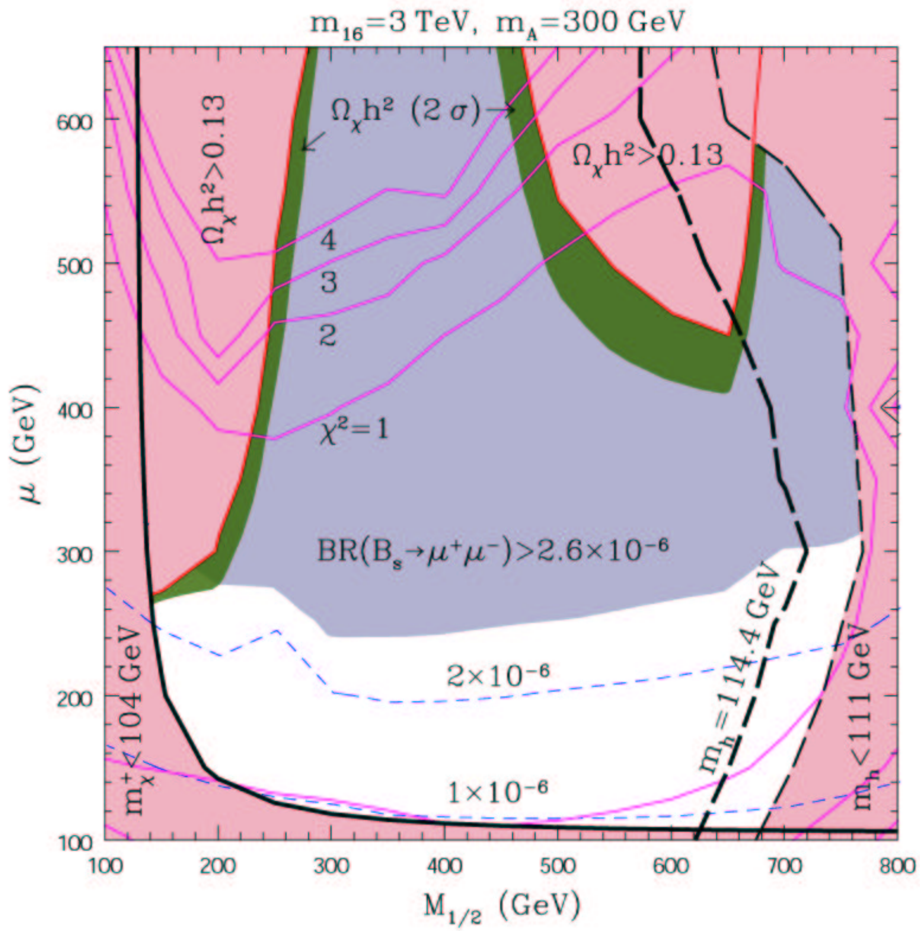


Test of the minimal supergravity model mSUGRA

Deviation of the muon anomalous magnetic moment, a_u, from the standard model prediction is correlated to an increased BR.

hep-ph/0108037

$SO(10)$ models, which accommodate neutrino masses and mixing

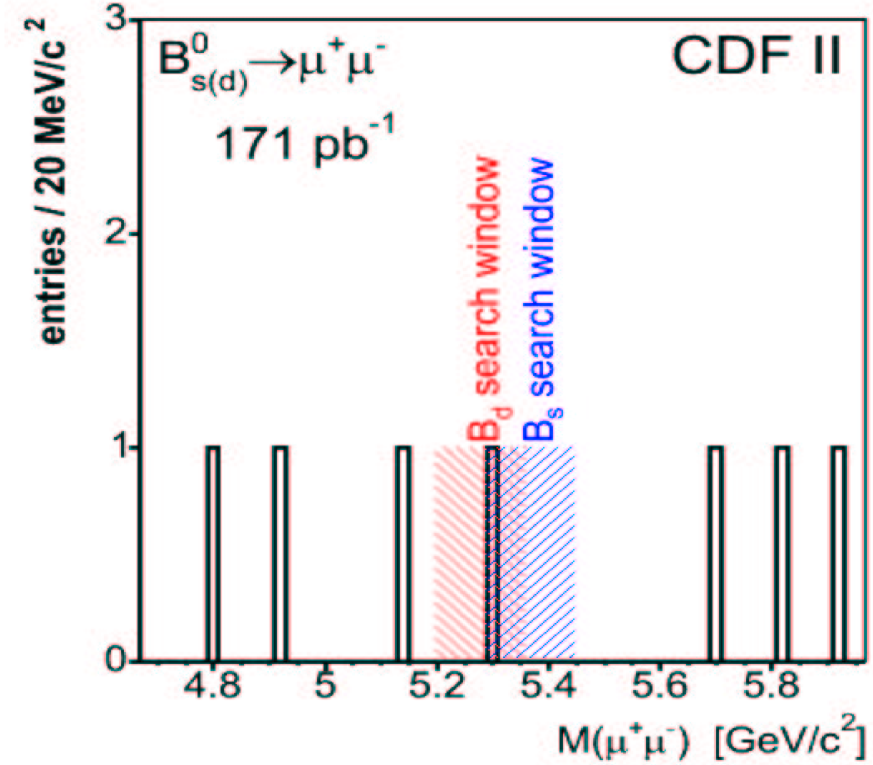


"White" region is excluded by the new CDF Run II results

→ Need higher masses for the CP odd Higgs mass, m_A

hep-ph/0304101

$B_{d,s} \to \mu^+\mu^-$ tests other Standard Model extensions



Run I limits (90% CL):

$\mathrm{BR}(B_s \to \mu\mu) < 2.0 \times 10^{-6}$

New Run II Results (90% CL):

$\mathrm{BR}(B^0_s \to \mu^+\mu^-) < 5.8 \times 10^{-7}$
$\mathrm{BR}(B^0_d \to \mu^+\mu^-) < 1.5 \times 10^{-7}$

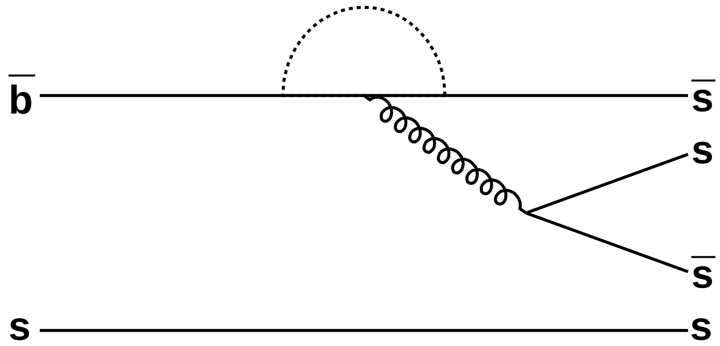
The B_d result matches Belle's best limit presented at LP03

The new B_s result is $3\times$ better that the best published result

$\rightarrow$ *Accepted for publication in Phys Rev Lett...*

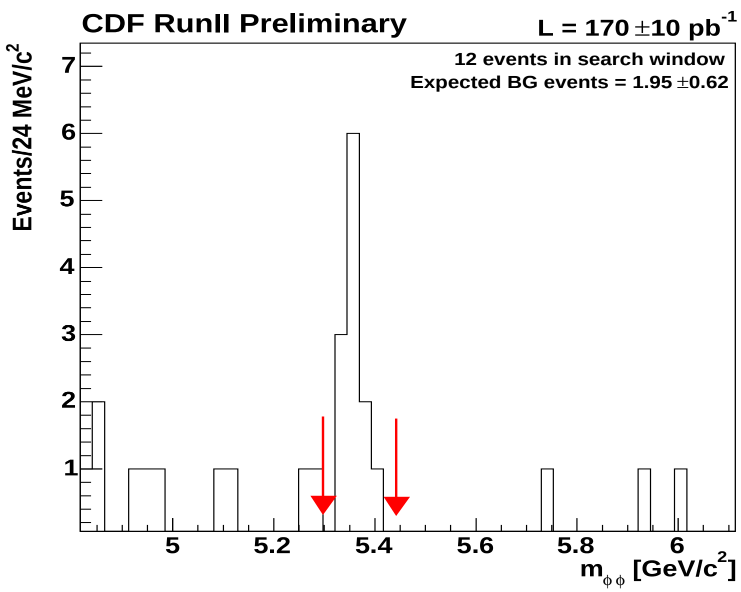
The BR limit can be further extended by increasing the acceptance and by reducing the background

First Observation of $B_s \to \phi\phi$



Decay through $b \to s\bar{s}s$

Interesting in light of possible anomalies reported by Babar/Belle
(CP violation in $B_d \to \phi K_s$)



BR predicted by QCD is 3.7×10^{-5} (hep-ph/0309136)

Have 12 candidates in about 180 pb^{-1} of data

Signal has a significance of 4.7 σ

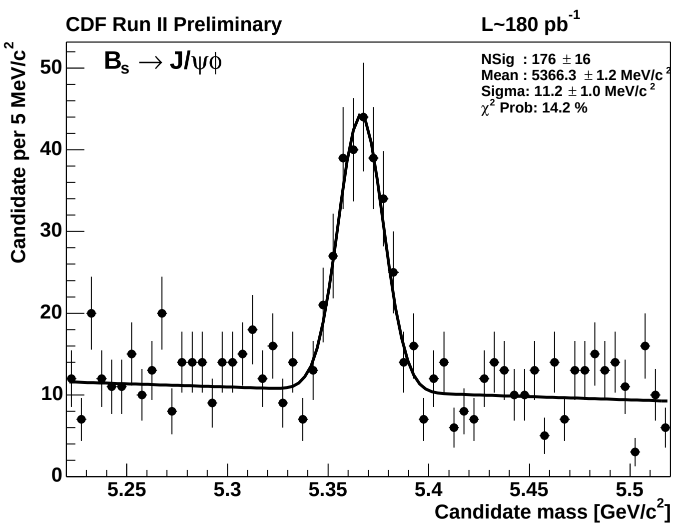
$$\text{BR}(B_s \to \phi\phi) = (1.4 \pm 0.6(stat) \pm 0.2(sys) \pm 0.5(\text{BR})) \times 10^{-5}$$

$B \to VV$ Polarization Amplitudes

One of the important objectives of Run II is to measure the lifetime difference $\Delta\Gamma$ between the CP eigenstates $B^0_{s,H}$ and $B^0_{s,L}$

An angular analysis based on transversity variables combined with a lifetime measurement permits one to separate the B_s odd and even CP final states

Prerequisite for $\Delta\Gamma_s$ and a test of factorization



$B_s \to J/\psi\phi$ (Worlds Best Results)

$A_0 = 0.767 \pm 0.045 \pm 0.017$

$A_{\parallel} = (0.424 \pm 0.118 \pm 0.013)e^{(2.11\pm0.55\pm0.29)i}$

$|A_{\perp}| = 0.428 \pm 0.104 \pm 0.014$

Measurement of B^0 Oscillations Using SST

First steps in measuring B_s mixing

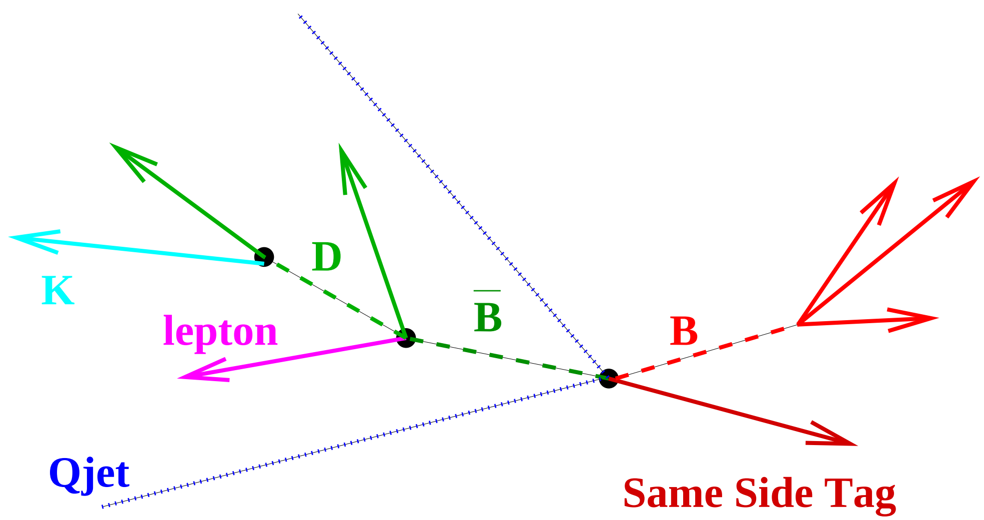
Determine the flavor (B vs $\bar{B}$) at time of production using Same Side Tagging

The SST method is based on expected flavor-charge correlations

Charge correlation between the B meson and charged tracks in it's vicinity are used to identify the B meson flavor.

Opposite Side Tagging

- Momentum weighted sum of the charge of the tracks for the opposite side jet
- Soft e or μ tag from simileptonic decay of opposite B (SLT)
- Charge of kaons opposite to the B decay (requires time of flight for particle ID)



Using fully reconstructed decays:

$$B^0 \to J/\psi K^{*0} \quad (J/\psi \to \mu^+\mu^-, K^{*0} \to K^+\pi^-)$$

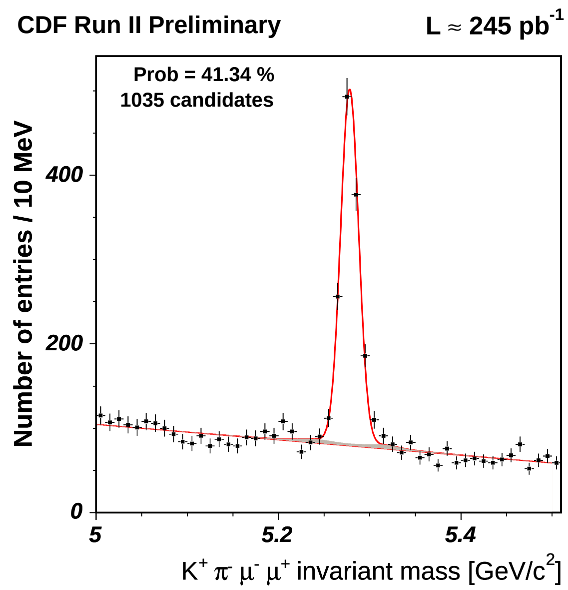
$$B^0 \to D^-\pi^+ \quad (D^- \to K^+\pi^-\pi^-)$$

Mixing parameter:

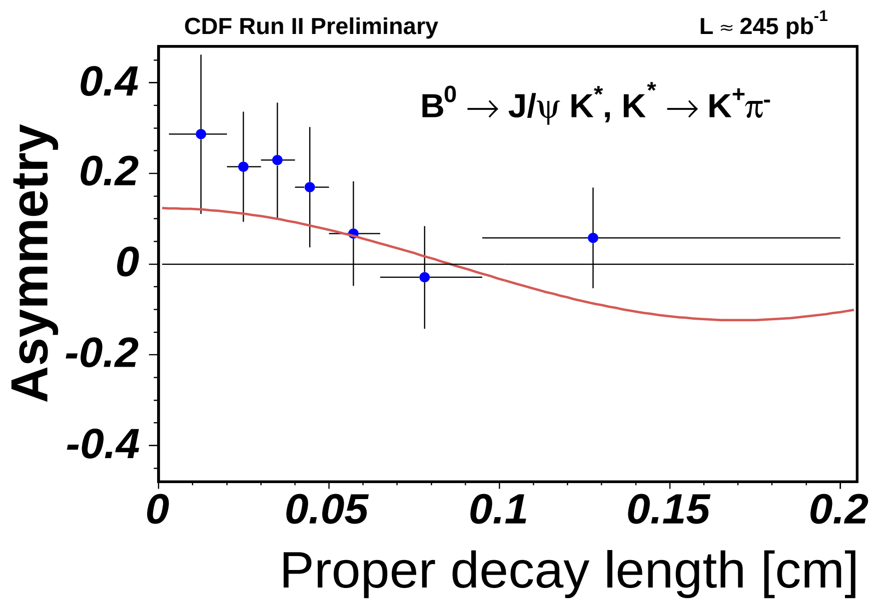
$\Delta m_d = 0.55 \pm 0.10 \pm 0.01 \quad \text{ps}^{-1}$

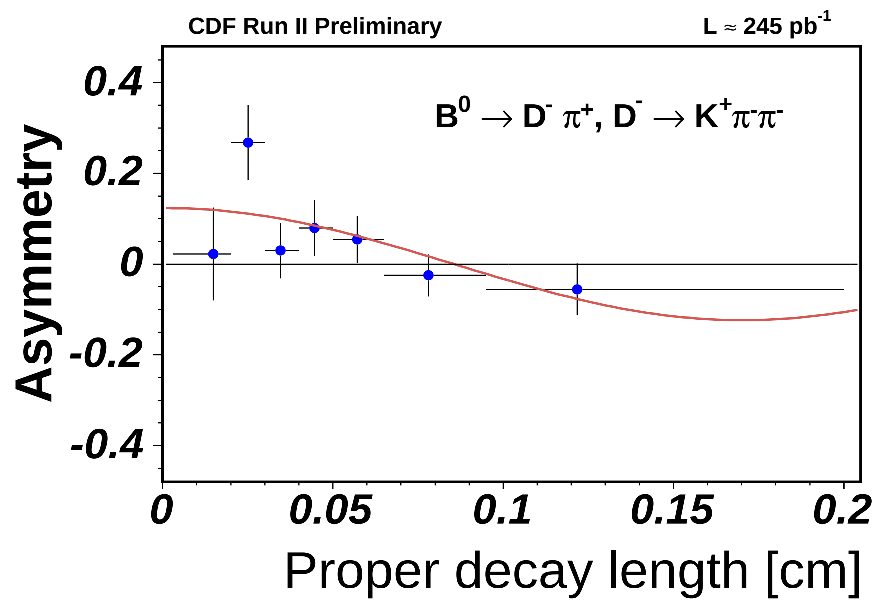
Dilution:

$D = 12.4 \pm 3.3\%$



Result of simultaneous fit

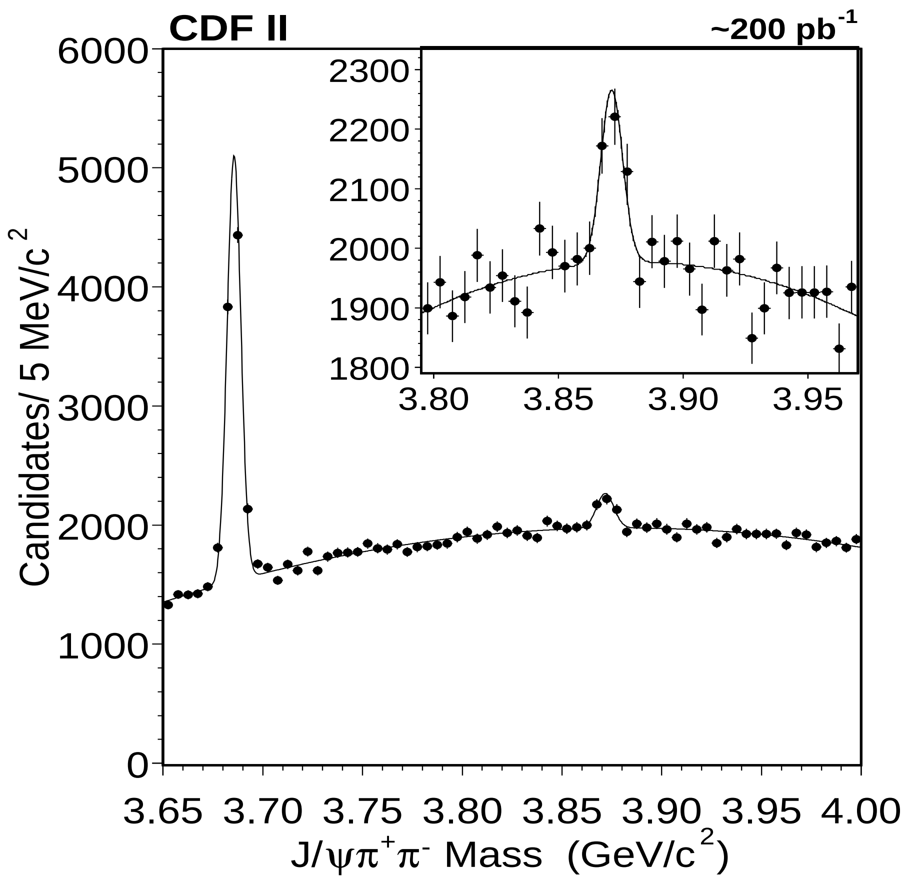




First Run II measurement of B^0 oscillations at CDF

Observation of the $X(3872)$ at CDF

CDF has provided the first confirmation of Belle's recent discovery of a narrow state, the $X(3872)$



$B \to XK \to J/\psi\pi^+\pi^-K$

At the Tevatron this state can be produced directly or via B decays.

CDF:
$M = 3871.3 \pm 0.7(stat) \pm 0.4(sys)$MeV

Belle:
$M = 3872.0 \pm 0.6(stat) \pm 0.5(sys)$MeV

Accepted for publication in Phys Rev Lett

$\to$ *Much interest in the interpretation of this new state*

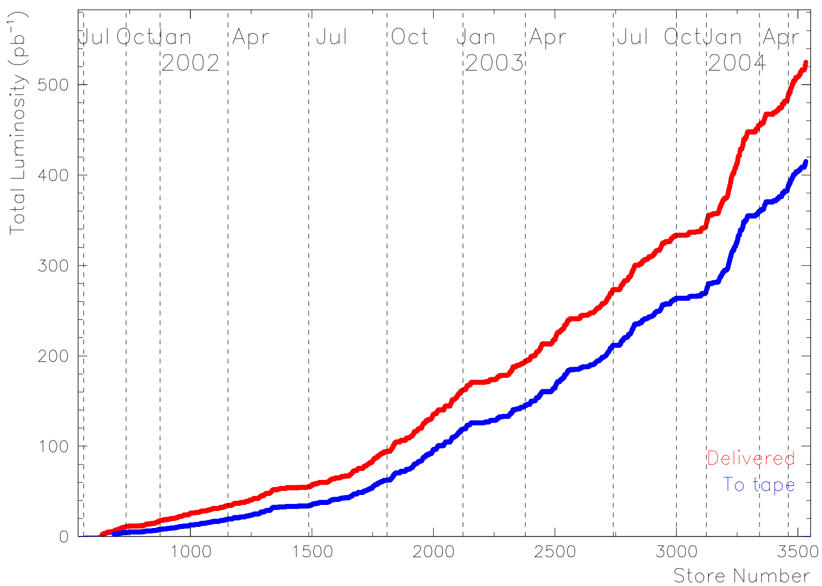
Publication Progress

- D_s, D^+ Mass Difference *Phys Rev D68, 072004, 2003*
- Search for $D \to \mu\mu$ *Phys Rev D68, 091101, 2003*
- Prompt Charm Cross Section *Accepted by Phys Rev Lett*
- Observation of $X(3872)$ *Accepted by Phys Rev Lett*
- Search for $B_{d,s} \to \mu^+\mu^-$ decays in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$TeV *Accepted by Phys Rev Lett*
- $D^0 \to \pi^-\pi^+/K^-K^+$ Relative Branching Ratio and Charge Asymmetry *Under internal publication review*
- Measurement of the J/ψ meson and b quark production cross sections in $p\bar{p}$ collision at $\sqrt{s} = 1.96$ TeV *Under internal publication review*
- $\Lambda_b \to \Lambda_c\pi$ Relative Branching Ratio *Under internal publication review*
- B Hadron Masses *Under internal publication review*
- $B_s \to D_s\pi$ Relative Branching Ratio *Under internal publication review*
- Search for Exotic $S = 2$ Pentaquark decaying to $\Xi\pi$ *Under internal publication review*

In addition to the many mature analyses there are many more analyses in progress

Work In Progress

- Polarization Amplitudes in $B \to VV$
- Branching Ratio and A_{CP} in $B^+ \to \phi K$
- B^0 Mixing with Same Side Tracks in Fully Reconstructed Decays
- Pentaquark Search in $\theta^+ \to pKs$
- Pentaquark Search in $\theta_c \to pD^*$
- $B_s \to VV$ lifetimes
- Moment Analysis
- B Hadron Masses
- $B^+ \to J/\psi\pi$ Branching Ratio
- Observation and Branching Ratio of $B_s \to \phi\phi$
- $B_c \to J/\psi\mu X$
- Soft electron reconstruction for $B_c \to J/\psi e X$
- Branching Ratio and Charge Asymmetry in $D^+ \to \pi^+\pi^-\pi^+$

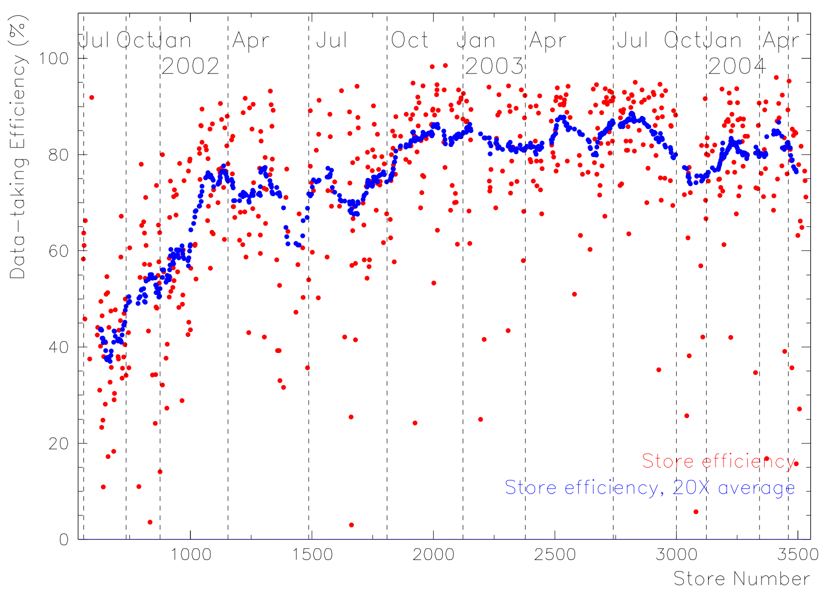


Tevatron is performing well

(05/26/04 18:18) Store 3534 set a new record with a luminosity of $77.4 \times 10^{30} cm^{-2} s^{-1}$ measured at CDF

Approaching $3-4\times$ the Run I usable dataset size.

$\rightarrow$ *Analyses presented here make use of up to* $\sim 250\text{pb}^{-1}$



CDF is collecting data with good efficiencies 80 - 90%

Very flexible trigger:

56 triggers at L1

117 triggers at L2

172 triggers at L3

Summary

- Tevatron is the world's highest energy collider allowing us to probe distance scales of $\sim 10^{-17}$ cm

- High energy jets allow us to search for new physics and provide input to theory yielding more precise calculations
  $\rightarrow$ *These improved calculations are not only important at the Tevatron but also at future experiments like the LHC.*

- The Tevatron is operating in a unique region of phase space
  $\rightarrow$ best place to study the high x gluon content of the proton

- Excess b production rates, one area that experiment and QCD predictions are not in good agreement, can be studied in more detail in Run II

- Expect a better understanding of the difference between the HERA and the Tevatron Pomeron

- CDF's world best branching ratio limits from $B_s \to \mu\mu$ place stringent limits on new physics (SUGRA, $SO(10)$, MSSM...)

- Many techniques that will be used to constrain the CKM matrix are well developed $\to$ world's best results for the B_s^0 and Λ_b masses and lifetimes

- First observation of the rare decay mode: $B_s \to \phi\phi$

- First confirmation of the new state $X(3872)$

- CDF is collecting data with high efficiencies and the Tevatron has been achieving record luminosities $\to$ *Many mature analyses are on track for publication and many more in the pipeline*

- *All made possible by a dynamic and energetic group able to adapt to changing conditions, working around the clock to make CDF a success*